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# Corequake and Shock Heating Model of the 5 March 1979 Gamma Ray Burst

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ABSTRACT

Ramaty et al. (1980) have proposed a model to account for the 5 March 1979 gamma ray burst in terms of a neutron star corequake and subsequent shock heating of the neutron star atmosphere. We elaborate on this model by examining the overall energetics and characteristics of these shocks, taking into account the  $e^+e^-$  pair production behind the shock. The effects of a dipole magnetic field in the shock jump conditions are also examined and it is concluded that the uneven heating produced by such a field can account for the temperature difference between pole and equator implied by the pulsating phase of the burst. The overall energetics and distribution of energy between  $e^+e^-$  pairs and photons appears to be in agreement with observations if this event is at a distance of 55 kpc as implied by its association with the Large Magellanic Cloud.

## I. INTRODUCTION

If the 5 March 1979 gamma ray burst is extragalactic as suggested by its association with the supernova remnant N49 in the Large Magellanic Cloud (LMC), unique problems are presented in understanding its radiation mechanism and energy source. Ramaty et al. (1980) and Ramaty, Lingenfelter and Bussard (1981) have proposed an  $e^+e^-$  synchrotron cooling and annihilation model for the radiation mechanism, the primary source of energy being gravitational released in the collapse of a neutron star core. This model can naturally account for the impulsive phase of the burst, presumably energized by the vibrations of the neutron star following the core collapse, which steepen into shocks upon reaching the steep surface density gradient. Such a core collapse can easily satisfy the energy requirements even if the source is in the LMC, a view further supported by independent arguments requiring that the spectrum above 500 keV is due to comptonization of soft photons (Liang 1981).<sup>1</sup>

In the present paper we accept the physical association of the event with the supernova remnant N49 in the LMC (Felten 1981) and further expand on the model of Ramaty et al. (1980) by studying in greater detail the characteristics of the strong gas shocks presumably responsible for powering the impulsive phase of the burst. Assuming complete thermodynamic equilibrium behind the shock (including the  $e^+e^-$  pairs), the postshock temperatures and positron densities are calculated for various values of the shock velocity, density and magnetic field, appropriate for neutron star envelopes. The corresponding luminosities and energy distribution between photons and pairs are then compared to observations and found in reasonable agreement. We

<sup>1</sup>Of all the observed gamma ray bursts, only two have been identified with known objects. One is the 5 March event in the LMC and the other, identified recently with Vela X-ray observations (Terrell et al. 1982), is consistent in direction with the binary pulsar SMC X-1 in the Small Magellanic Cloud.

further propose that the subsequent 8 s pulsations are due to the uneven surface heating resulting from the neutron star's dipole magnetic field. The polar regions, having approximately radial fields should experience stronger shocks, and hence higher postshock temperatures and luminosities than the equatorial regions where the field is approximately parallel to the surface. Within the framework of the above assumptions, it is found that reasonable values of the field can account for the observed temperature difference inferred from the peaks and valleys of the pulsating phase.

An earlier suggestion that quakes within the crust of nearby neutron stars power galactic gamma ray bursts was made by Fabian, Icke and Pringle (1976). This model assumed that quakes, releasing about  $10^{39}$  erg, occur within 1 km from the neutron star surface and produce galactic gamma ray bursts at a typical distance of 100 pc.

In Section II the salient features of the burst are critically reviewed while in Section III the details and justification of the assumptions used in the present paper are given. Section IIIA deals with the question of the corequake and the overall energetics associated with it. In Section IIIB the Rankine-Hugoniot conditions for shocks propagating in the neutron star atmosphere, including the effects of the radiation field,  $e^+e^-$  pairs and magnetic field, are written down and solved numerically. The results are summarized in Section IIIC and are used to account for the pulsating phase of the burst in Section IV. Finally in Section V the overall results are evaluated and conclusions are drawn.

## II. DESCRIPTION OF 5 MARCH GAMMA RAY BURST

The 5 March 1979 gamma ray burst appears to be of a different class than the other gamma ray bursts thus far reported. The reasons for presuming this

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are the following:

(1) The peak energy flux in the impulsive phase is  $\sim 4.5 \times 10^{-4}$  erg cm $^{-2}$  (Mazets et al. 1982), at least an order of magnitude greater than any other observed burst.

(2) Strong positional identification (Cline et al. 1980, 1982; Felten 1981) with the supernova remnant, N49, in the LMC places (if this association is not coincidental) the source at 55 kpc and implies a luminosity of  $\sim 1 \times 10^{45}$  erg s $^{-1}$  for the initial pulse (Mazets et al. 1982). If the other gamma ray bursts are galactic, as implied by the observed frequency distribution (Rothenflug and Durouchoux 1981, Jennings 1982), the 5 March event is over 4 orders of magnitude more luminous than the most intense galactic burst and produced a total of  $\sim 5 \times 10^{44}$  erg (Mazets et al. 1979).

(3) The impulsive phase of the 5 March event has a very short rise time ( $< 2 \times 10^{-4}$  s, Cline et al. 1980) and a duration ( $\sim 0.15$  s), shorter than most other bursts.

(4) Following the impulsive phase, clear pulses are observed for at least three minutes with a period of  $8.0 \pm 0.05$  s. The average pulsed flux is about 2 orders of magnitude less than the impulsive peak ( $\sim 3.6 \times 10^{42}$  erg s $^{-1}$ ) and decreases approximately exponentially with an e-folding time of  $\sim 50$  s (Mazets et al. 1979). The total energy emitted during the oscillating phase is  $\sim 2$  times as great as emitted in the initial pulse. The pulses show an interpulse of lower intensity that is strongly reminiscent of pulsar pulse profiles and implies emission from the magnetic poles of a rotating neutron star. It must be pointed out, however, that no observed pulsar has a period as long as 8 s and if the 5 March burst is associated with N49, whose age is  $\sim 10^4$  years, a much shorter period would be expected if an object similar to observed radio pulsars produced the burst (Barat et al. 1979).

(5) The 5 March event is also unique in that it was followed by three other bursts with delays of 0.60, 29 and 50 days (6 March, 4 April and 24 April) and intensities of 3, 1 and 0.5 percent respectively of the 5 March event (Cline 1982). The positional data on these bursts are less precise than 5 March but are consistent with N49 (more recent observations show a total of ~10 bursts from this direction (Mazets 1983)).

(6) The energy spectrum of the 5 March event is considerably softer than typical bursts with most emission at energies below the line feature centered at about 430 keV.

In addition to the above unique features, the initial pulse of the 5 March event shows a broad emission line centered at 430 keV with FWHM of ~150 keV (Mazets et al. 1982). This feature has been seen in several of the most intense gamma ray bursts (Mazets et al. 1981) and has been interpreted as 511 keV annihilation radiation redshifted in the gravitational field of a neutron star with  $M \sim 1M_{\odot}$ , and  $R \sim 10^6$  cm which implies  $z = (1-2GM/Rc^2)^{-1/2} - 1 = 0.19$  (Mazets et al. 1979 and Ramaty et al. 1980). The energy flux in the line is about 7% of the total impulsive flux ( $\sim 7 \times 10^{43}$  erg s<sup>-1</sup>, Mazets et al. 1982).

### III. THE MODEL

Fig. F1 shows the time history of the 5 March burst. The contrast between the very intense, very sharp initial pulse and the slowly decaying 8 s pulsations lead us (along with Ramaty et al. 1980) to propose the following scenario to account for the main characteristics of this burst. First, the energy is released in a phase transition in the neutron star core, releasing a small fraction of the  $10^{53}$  erg in total binding energy as vibrations that propagate to the surface at a sizable fraction of the speed of light. Second, the initial pulse is generated when the vibrations produce strong, radiation dominated, gas shocks in the atmosphere. Third, the slowly decaying pulsating

phase is due to the uneven heating of the neutron star surface due to its dipole magnetic field. The  $< 2 \times 10^{-4}$  s rise time of the initial pulse is characteristic of the energy release time of the phase transition. The  $\sim 100$  ms decay time of the initial pulse has been shown by Ramaty et al. (1980) to be consistent with gravitational radiation damping of non-radial vibrations in a  $\sim 1 M_\odot$  neutron star. The  $\sim 50$  s decay time of the pulsations could be either the cooling time of the surface layer by conduction to the core and radiation at the surface or the damping time of the radial vibrations by the  $\{\}$  process (Langer and Cameron 1969).

#### (A) Corequake

Matter at or near nuclear densities is composed mainly of neutrons. At a critical density about twice nuclear density, a new state is thought to exist containing a condensed charged pion wave (Hartle, Sawyer, and Scalapino 1975). This pion condensate has a lower energy per baryon and a significantly softer equation of state than nuclear matter and will affect the mechanical properties of neutron stars, such as the mass radius relation. In addition, the possibility exists that if the core density slowly increases beyond the critical density for pion condensation, a supercompressed, metastable, state of neutron matter will be produced (Haensel and Proszynski 1982 and Haensel and Schaeffer 1982). The slow increase in core density could occur through mass accretion,<sup>2</sup> by reduced centrifugal forces due to a slowing rotation rate, or by cooling (Baym 1981). At some point a phase transition could occur from

<sup>2</sup>If accretion produces the increase in core density, Haensel and Schaeffer have estimated that more than  $10^{-2} M_\odot$  must be accreted before the phase transition to the pion condensate occurs. If the supernova remnant, N49, is  $\sim 10^4$  years old, this implies an accretion rate greater than  $10^{-6} M_\odot \text{ yr}^{-1}$ . This is over  $10^4$  greater than the upper limit on steady state accretion for N49 deduced from X-ray observations (Helfand and Long 1979) and seems to exclude accretion as the sole mechanism for increasing the core density unless a highly variable accretion process occurred.

the normal (but supercompressed) non-pion condensed state to the pion condensed state. This transition, or minicollapse, would result in a large release of energy.

Haensel and Proszynski (1982) and Haensel and Schaeffer (1982) have calculated in a semi-phenomenological way the basic properties of this collapse. These properties depend strongly on the equation of state used and due to the uncertainty in models of dense matter are by no means precisely known. However, for what the above authors consider to be the most realistic model, they find the following:

- (1) The radius of a collapsing neutron star of  $\sim 0.7 M_{\odot}$  decreases by  $\sim 10$  m.
- (2) The upper limit for the time scale of the collapse should be approximately the free fall time or  $(GM/R^3)^{(-1/2)} \sim 10^{-4}$  s for  $R = 10$  km, consistent with the rapid rise time of the 5 March burst.
- (3) The energy release as estimated by Haensel and Proszynski (1982) would be  $\sim 10^{48}$  erg and would mainly go into heating the neutron star core. The proportion that would go into vibrational energy is unknown, but if the amplitude of the vibration is roughly the change in the radius of the star (i.e.,  $\sim 10$  m) then the oscillatory energy,  $E_{\text{osc}}$ , can be estimated from dimensional considerations (Zel'dovich and Novikov 1971, p. 366);

$$E_{\text{osc}} \sim 10^{53} (M/M_{\odot}) (\delta R/R)^2 \text{ erg.} \quad (1)$$

If  $\delta R/R \sim 10^{-3}$  as suggested, the vibrational energy would be  $\sim 10^{47}$  erg and only a small fraction ( $\sim 0.01$ ) would be sufficient to account for the energetics of the burst. For such small amplitudes, the proportion of vibrational energy that is lost due to viscosity in the core is insignificant and implies that the damping of the vibrations is from the transport of energy

to the surface by shock waves, the emission of gravitational waves and the  $\gamma^-$  process as mentioned above.

The supernova remnant, N49, was observed in soft X-rays  $\sim$  38 days and  $\sim$  2 years after the burst and only upper limits for the flux were obtained (Helfand and Long 1979, Pizzichini et al. 1982). However, even though  $\sim 10^{48}$  erg are released by the corequake, it is likely that the only observable consequence will result from the small fraction of this energy that is rapidly dissipated in the thin surface layer when the vibrations steepen into shocks and produces the gamma ray burst. This layer will be thin because, as suggested by Fabian et al. (1976), even though the thermal conductivity of neutron star material is very high, a shock will not dissipate energy unless the shock temperature exceeds the Fermi temperature. This will start to occur when the shocks approach the nondegenerate outer crust, i.e., when the density drops below  $\sim 2.4 \times 10^8 T^{3/2} \text{ gm cm}^{-3}$  (Lang 1974, p. 253). Even if thermal energy is stored at  $10^{10}$  K (where neutrino losses begin to be important) it implies that only densities less than  $\sim 2.4 \times 10^7 \text{ gm cm}^{-3}$  are heated. This represents a very thin skin of less than  $10^{20}$  gm (Soyer 1980) with an energy content much less than the energy of the burst. Therefore, energy must be continually supplied to the surface by the vibrations and the surface temperature will decay with essentially the same decay time as the vibrations. If this is  $\sim 50$  s, the surface will not have been observable in soft X-rays  $\sim$  38 days after the burst (Helfand and Long 1979). In addition, it is unlikely that the bulk heating of the core would have been observable if the event occurred in the LMC, since  $10^{48}$  erg distributed among  $1 M_\odot$  produces an increase in particle energy of only  $\sim 1/2$  keV per nucleon. This implies a temperature of less than  $6 \times 10^6$  K and is at the lower limit of detectability in soft X-rays (K. Hurley, private communication) only if significant losses

did not occur by neutrino emission or gravitational radiation.

(4) The lifetime of the metastable state depends critically on the core density. The important result is that for cold neutron stars, the transition can occur only once and at the point when the core density increases from 0.293 to  $0.294 \text{ fm}^{-3}$  ( $1 \text{ fm} = 10^{-13} \text{ cm}$ ). The age of the star when this occurs would depend on how close to the critical density the star was born and on the rate at which the core density increased. The phase transition could occur at any time from very young to never. In other words, the minicollapse would be both very energetic and very rare, a natural explanation for the lack of galactic gamma ray bursts of the size of the 5 March event.

(5) No disruption of the star results.

(6) The minicollapse would lower the moment of inertia by 0.1%, many orders of magnitude greater than that implied by radio pulsar glitches, and cause a speed-up in the rotation rate (Haensel and Proszynski 1982). The subsequent bursts observed at the 5 March location could be the result of crustquakes, as envisioned by Fabian et al. (1976), triggered by readjustments of the star to its new equilibrium configuration. The total energy released in these subsequent bursts, though substantial ( $\sim 10^{42} \text{ ergs}$ ), is a small fraction ( $\sim 10^{-3}$ ) of the total burst energy and could conceivably be accounted for in this manner.

#### (B) Impulsive Phase

The spectrum observed in the first 4 s of the 5 March gamma ray burst (Mazets et al. 1979) and assumed to be indicative of the spectrum of the initial 150 ms spike shows a soft, approximately exponential ( $kT \sim 35 \text{ keV}$ ) spectrum with a clear emission feature, interpreted as redshifted  $e^+e^-$  annihilation radiation, centered at  $\sim 430 \text{ keV}$ . We propose this emission is produced in the strong, radiation dominated, atmospheric shocks that result

when the vibrations from the neutron star corequake steepen while propagating in the sharp surface density gradient. The shocks will cause the surface to expand at a considerable fraction of the speed of light, compressing the gas at the surface and producing gas shocks.<sup>3</sup>

(1) Shock jump conditions

Assuming a reference frame where the shock is stationary, the steady state jump conditions relating conservation of proton, momentum, energy and magnetic fluxes ahead of (subscript 1) and behind (subscript 2) the shock, allowing for the production of pairs from the equilibrium photon field behind the shock, are as follows:

$$n_{p1}u_1 = n_{p2}u_2 \quad (2)$$

$$n_{p1} \frac{m_p u_1^2}{p_1} + n_{p1} k(T_{p1} + T_{e1}) + \frac{1}{3} a T_{e1}^4 + \frac{B_1^2}{8\pi} \quad (3)$$

$$= n_{p2} \left( \frac{m_p u_2^2}{p_2} + kT_{p2} \right) \quad (\text{protons})$$

$$+ n_{e2} \left( \frac{m_e u_2^2}{p_2} + kT_{e2} \right) \quad (\text{electrons})$$

$$+ n_{\gamma} \left( \frac{m_e u_2^2}{p_2} + kT_{e2} \right) \quad (\text{positrons})$$

$$+ \frac{1}{3} a T_{e2}^4 + \frac{B_2^2}{8\pi} \quad (\text{photon and magnetic fields})$$

$$\left[ \frac{1}{2} n_{p1} \frac{m_p u_1^2}{p_1} + \gamma' n_{p1} k(T_{p1} + T_{e1}) + 4 a T_{e1}^4 + \frac{B_1^2}{4\pi} \right] u_1 \quad (4)$$

<sup>3</sup> The speed of sound,  $s$ , is determined from  $s = (dP/d\rho)^{(1/2)}$  where  $P$  is the pressure. The equation of state for a degenerate, nonrelativistic neutron gas is given by (Lang 1974, p. 265);  $P \sim 10^{10} \rho^{(5/3)}$  dyn cm<sup>-2</sup> and for  $\rho \sim 3 \times 10^{14}$  g cm<sup>-3</sup> we have  $s \sim 9 \times 10^9$  cm s<sup>-1</sup>.

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$$\begin{aligned}
 &= [\frac{1}{2} n_p m_p u_2^2 + \gamma' n_p k T_p] \\
 &+ \frac{1}{2} n_e m_e u_2^2 + \gamma' n_e k T_e] \\
 &+ \frac{1}{2} n_+ m_e u_2^2 + \gamma' n_+ k T_e] \\
 &+ 4 \alpha T_e^4 + \frac{B^2}{4\pi}] u_2
 \end{aligned}$$

$$B_1 u_1 = B_2 u_2 \quad (5)$$

where

$$\gamma' = \frac{\gamma_e}{\gamma_e - 1} \quad (6)$$

$$\gamma_e = \frac{\gamma_e}{\gamma_e - 1} \quad (7)$$

and  $\gamma$  ( $\gamma_e$ ) is the ratio of specific heats for protons (electrons).  $\gamma$  is assumed to equal 5/3 and  $\gamma_e$  varies from 5/3 to 4/3 depending on the thermal kinetic energy of the electrons according to the relation,  $\gamma_e = 1 + (1/3)[(1+2w')/(1+w')]$  where  $w' = m_e c^2 / [(3/2)k T_e]$ .

In the above equations,  $n_p$  ( $n_e$ ) is the proton (electron) number density,  $n_+$  is the positron number density,  $u_1$  ( $u_2$ ) is the bulk plasma flow velocity ahead of (behind) the shock,  $m_p$  ( $m_e$ ) is the proton (electron) rest mass,  $T_p$  ( $T_e$ ) is the proton (electron) temperature,  $B$  is the magnetic field (assumed perpendicular to the shock normal),  $a = 7.56 \times 10^{-15} \text{ erg cm}^{-3} \text{ deg}^{-4}$ , and  $k = 1.38 \times 10^{-16} \text{ erg deg}^{-1}$ . The terms  $n_{el} m_e u_1^2$  and  $1/2 n_{el} m_e u_1^3$  have been omitted

from the left hand sides of equations (3) and (4) respectively since  $n_{e1} = n_{p1}$  and they are smaller than the corresponding proton terms by the factor  $m_e/m_p$ . These terms are included on the right hand sides since the production of pairs allows  $n_{e2}$  to become greater than  $n_{p2}$ .

The assumptions made in writing these equations are the following: (a) The shock is locally plane, (b) the gas is ideal and fully ionized, (c) the flow velocities,  $u_1$  and  $u_2$ , are nonrelativistic, (d) charge neutrality is maintained (i.e.  $n_e = n_+ = n_p$ ), and (e) equilibrium is established between protons, electrons, the photon field, and pairs (i.e.  $T_p = T_e = T_\gamma$  on a time scale short compared to (i) any losses such as radiation (i.e., we assume optical thickness  $\gg 1$ ) and (ii) the transit time of the shock through the surface density gradient.

The pair density behind the shock is calculated, assuming equilibrium between creation and annihilation at the downstream temperature,  $T_{e2}$ , by integrating over the Fermi-Dirac momentum spectrum (Clayton 1968, p. 274), i.e.,

$$n_{e2}^+ = \frac{1}{\pi^2} \left( \frac{m_e c}{h} \right)^3 \int_1^\infty \frac{w(w^2-1)^{1/2}}{\exp(Gw + \phi) + 1} dw \quad (8)$$

where  $G = m_e c^2 / (kT_{e2})$ ,  $w$  = the total energy of electrons or positrons in units of  $m_e c^2$  and  $\phi$  is the chemical potential in units of  $kT_{e2}$ . The parameter,  $\phi$ , is determined iteratively from the conservation of charge  $n_{e2} - n_+ = n_{p2}$  condition, and it is approximately 0.1.

The above system of equations is solved numerically for given input parameters,  $n_{p1}$ ,  $u_1$ ,  $T_{p1}$ , and  $B_1$ .

## (2) Time scales

The relevant time scales for this problem are the following:

(a) The equilibration time of electron and proton temperatures is given approximately by (Zel'dovich and Raizer 1966, p. 421)

$$t_{ep} \sim 8 \times 10^{-13} T_9^{3/2} n_{27}^{-1} \text{ s} \quad (9)$$

where  $n_{27}$  is the proton number density in units of  $10^{27} \text{ cm}^{-3}$ ,  $T_9$  is the electron temperature in units of  $10^9 \text{ K}$  and a value of 10 is used for the Coulomb logarithm. The equilibration time between electrons and positrons is about 100 times less.

The Compton scattering time is given by

$$t_c \sim 1.5 \times 10^{-38} \sigma_T^{-1} T_9^{-1/2} \sim 2.25 \times 10^{-14} T_9^{-1/2} \text{ s} \quad (10)$$

where  $\sigma_T$  is the Thomson cross section,  $\sigma_T \sim 6.65 \times 10^{-25} \text{ cm}^2$ .

(c) The synchrotron loss time (Lang 1974, p. 29) is

$$t_s \sim 4 \times 10^{-15} B_{12}^{-2} T_9^{-1} \text{ s} \quad (11)$$

where  $B_{12}$  is the magnetic field in units of  $10^{12} \text{ G}$ .

(d) The annihilation time is

$$t_a \sim \frac{1}{\alpha n_+} \sim 1.3 \times 10^{-13} n_{27}^{-1} \text{ s} \quad (12)$$

where  $\alpha$  is the annihilation rate coefficient and is approximately constant and equal to  $7.5 \times 10^{-15} \text{ cm}^3 \text{ s}^{-1}$  (Bussard, Ramaty and Drachman 1979), and  $n_{+27}$  is the positron number density in units of  $10^{27} \text{ cm}^{-3}$ .

(e) The plasma frequency is

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$$v_p = \left( \frac{n_e e^2}{\pi m_e} \right)^{1/2} \sim 9 \times 10^3 n_e^{1/2} \text{ Hz}$$

or

$$t_p \sim 3.5 \times 10^{-18} n_{e27}^{-1/2} \text{ s} \quad (13)$$

where  $n_{e27}$  is the electron number density in units of  $10^{27} \text{ cm}^{-3}$ .

(f) The electron gyroperiod is

$$v_e^{-1} \sim 8 \times 10^{-20} B_{12}^{-1} \gamma \text{ s} \quad (14)$$

where  $\gamma = (1 - (v/c)^2)^{-1/2}$ .

(g) The time for the shock to move one gravitational scale height ( $h_g$  600  $T_9$  cm, Liang (1982)), is

$$t_g \sim 2 \times 10^{-8} T_9^{3/2} \text{ s} \quad (15)$$

where  $\beta_{sh} = u_1/c$ . This is large compared to the time scales given above and justifies the assumption that steady state conditions are obtained as the shocks move down the atmospheric density gradient.

(h) The large temperature gradients produced at the surface will cause the shocks to be convective as pointed out by Fabian et al. (1976). They have estimated a lower limit on the convective time scale,  $t_{cv}$ , of

$$t_{cv} \geq 4 \times 10^{-5} \text{ s.} \quad (16)$$

The presence of a strong magnetic field is expected to inhibit convection and may make  $t_{cv}$  considerably longer (Proctor and Weiss 1982). Since energy from lower hotter layers will be supplied to the rapidly cooling emission layer on this time scale,  $t_{cv}$  may be expected to determine intensity fluctuations rather than the vibrational frequency or synchrotron cooling time. The fine time structure of the 5 March burst has been examined by Barat et al. (1983) and some evidence of quasi-periodic,  $\sim 25$  ms fluctuations is seen.

The synchrotron loss time is considerably less than the equilibration time for electrons and protons implying that the electron temperature immediately behind the shock will be less, due to synchrotron cooling, than the proton or photon temperatures contrary to our assumption. However, as long as the optical depth remains  $\gg 1$ , any difference in temperature will not seriously affect the results of the shock calculation since the shock is radiation dominated and, as shown below, the kinetic energy of electrons and positrons amounts to less than 5% of the total kinetic energy behind the shock. Also, as suggested by Liang (1981), collective effects, whose characteristic times,  $t_p$  and  $v_e^{-1}$ , are very short, may be important for maintaining equilibrium. In addition,  $t_s \ll t_a$  implying, as suggested by Ramaty et al. (1980), that pairs will annihilate after losing a significant fraction of their kinetic energy by synchrotron emission and hence produce an  $e^+ - e^-$  annihilation feature corresponding to a cooler temperature, as observed.

### (3) Input parameters

(a) At temperatures much below  $10^9$  K, the shocks are dominated by the ram pressure of the upstream fluid and are essentially independent of the upstream temperature. After the atmosphere is heated by the first shocks to  $10^9$  K, subsequent shocks will be weakened as discussed below.

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(b) We assume  $B_1$  to be  $10^{11}$  G, consistent with pulsar models, and the magnetic field configuration to be approximately dipolar.

(c) The upstream flow velocity,  $u_1$ , is essentially the velocity with which the neutron star surface expands under the influence of the internal vibrations and surface layer shocks. This will depend on the strength of the vibrations, the density gradient at the surface, the sound speed in the crust material, as well as the gravitational potential and, therefore, the mass and radius of the star. None of these quantities are particularly well known, but we assume  $u_1$  to have moderate, nonrelativistic velocities in the range  $4 \times 10^4$  -  $10^5$  km s<sup>-1</sup> considered to be typical for neutron stars.

(d) The upstream density,  $n_{p1}$ , is the unshocked gas density at the star surface.<sup>4</sup>

If, for the sake of concreteness, we assume that  $\sim 1/4$  of the surface area,  $A$ , of a 10 km radius neutron star ( $A \sim 3 \times 10^{12}$  cm<sup>2</sup>) produces a shock with an energy flux,  $F_{sh}$ , then, for cold upstream material,  $n_{p1}$  and  $u_1$  must satisfy the following condition:

$$\frac{1}{2} n_{p1} m_p u_1^3 A \sim F_{sh} \quad (17)$$

or

$$\rho_1 u_1^3 \sim 6.7 \times 10^{-13} F_{sh} \text{ (cgs units)} \quad (18)$$

where  $\rho_1 = n_{p1} m_p$ .

### (C) Results

Figs. 2, 3 and 4 show the temperature,  $T_{e2}$ , positron density,  $n_+$ , and

<sup>4</sup>When the strong internal shocks reach the surface, the surface layer will be vaporized and the atmosphere will consist of whatever gas was present prior to the shocks plus the topmost surface layer.

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compression ratio,  $r$  (defined as  $u_1/u_2$ ), plotted against the unshocked atmospheric density,  $\rho_1$ . For example, with  $F_{sh} = 10^{45}$  erg  $s^{-1}$ ,  $u_1 = 10^5$  km  $s^{-1}$  and  $\rho_1 = 670$  g  $cm^{-3}$ , the shock jump conditions yield  $n_+ = 9 \times 10^{27}$   $cm^{-3}$ ,  $T_{e2} = 1.6 \times 10^9$  K,  $r = 9$  and  $B_2 = 9 \times 10^{11}$  G. For the above values, the distribution of energy flux behind the shock is divided as follows (see Table 1): photons 65%, magnetic field 23.5%, electrons 2.5%, positrons 2%, protons 2% and the rest mass energy flux of the pairs, 5%. For a given shock energy flux,  $F_{sh}$ , the resulting downstream values of  $n_+$  and  $T_{e2}$  depend weakly on the upstream density,  $\rho_1$ , indicating that the shock is radiation dominated. The effect of an upstream temperature of  $10^9$  K is also shown in Figs. 3 and 4.

For a given shock velocity,  $u_1$ , the increase in upstream temperature results in weaker shocks (i.e., lower compression ratio) and hence less efficient dissipation of the vibrational energy. For upstream temperatures greater than the corresponding postshock temperatures,  $T_{el}$ , no shock results and the material must cool radiatively before the energy of the next shock is dissipated.

The effects of the magnetic field on  $n_+$ ,  $T_{e2}$  and  $r$  can be significant when  $\rho_1 u_1^2 \leq B_1^2/8\pi$ , as indicated by the dashed lines of Figs. 2, 3 and 4, which give the values of the above quantities in the absence of the magnetic field. In addition, as mentioned above, the magnetic field is necessary for cooling the electrons before they annihilate and hence produce a narrow annihilation feature.

The observed energy flux emitted in the initial pulse is divided between the  $e^+e^-$  annihilation feature and the continuum and totals about  $2 \times 10^{45}$  erg  $s^{-1}$ . The annihilation flux is about  $7 \times 10^{43}$  erg  $s^{-1}$  yielding a line to continuum flux ratio of 0.07. The density of cold positrons needed to produce the annihilation flux is (see equation 4)

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$$2n_e m_e c^2 Au_2 = 7 \times 10^{43} \text{ erg s}^{-1} \quad (19)$$

while the temperature needed to provide the continuum flux in the photon field, assuming blackbody emission is

$$4\pi T_{e2}^4 Au_2 = 9.3 \times 10^{44} \text{ (cgs units).} \quad (20)$$

Therefore, the necessary condition to produce the observed line to continuum flux ratio is

$$\frac{n+27}{T_9^4} = 1.4. \quad (21)$$

Table 1 shows the above ratio for various values of the shock luminosity,  $F_{sh}$ , and for a reasonable range in shock velocities. For  $F_{sh} = 10^{45} \text{ erg s}^{-1}$ , corresponding to the luminosity of the 5 March event the predicted ratio is between 1.3 and 1.5 in good agreement with the value demanded by equation (21).

#### IV. PULSATING PHASE

The 8 s pulsations shown in Fig. 1 can be most naturally explained, we feel, by emission from the unevenly heated surface (due to the dipole magnetic field) of an obliquely aligned, rotating neutron star. The reasons are the following:

- (1) The clear pulses with interpulses precisely  $180^\circ$  out of phase are a distinctive signature of emission from a non-uniformly heated, rotating star (Barat et al. 1979, Mazets et al. 1979, Terrell et al. 1980) and indicates that global heating of the star has taken place. If the magnetic field axis

is not aligned with the rotation axis, hot magnetic poles will sweep past the observer twice for each rotation. If the line of observation is at an angle other than  $90^\circ$  with the rotation axis, one pole will produce a more intense pulse than the other.

(2) The first four main pulses have an average value of  $kT = 35.45$  keV or  $T \sim 4 \times 10^8$  K (Mazets et al. 1982). If we assume blackbody emission at this temperature, an area aligned perpendicular to the line of sight equal to 20% of the surface area of a 10 km radius neutron star will have a luminosity of  $\sim 3.6 \times 10^{42}$  erg s $^{-1}$ . This is approximately equal to the observed pulsed luminosity assuming a distance of 55 kpc. The actual emitting area of the star will be somewhat greater depending on the angle between the line of sight and a line from the center of the star through the emitting area.

(3) The difference in temperature between the poles and equatorial regions as inferred from the pulse peak to valley intensity ratio can be naturally accounted for by the dipole magnetic field. At the poles, the field is approximately perpendicular to the shock surface and no compression of the field occurs across the shock. In the equatorial regions the field is parallel to the shock surface and will be compressed, absorbing on the order of 50% of the shock energy (see Table 1 for  $F_{sh} = 10^{43}$  erg s $^{-1}$ , a value consistent with the luminosity of the pulsating phase) and resulting in a lower post shock temperature. From Fig. 1 we estimate that

$$\frac{I_{\text{poles}}}{I_{\text{eq}}} \sim 3 - 6 \propto \left(\frac{T_{\text{poles}}}{T_{\text{eq}}}\right)^4 \quad (22)$$

implying that

$$\frac{T_{\text{eq}}}{T_{\text{poles}}} \sim 0.7 \quad (23)$$

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In Fig. 5 the ratio of downstream temperatures with and without a magnetic field are calculated for several shock velocities. These calculations use the same simplifying assumptions stated above with a constant shock luminosity,  $F_{sh} = 10^{43} \text{ erg s}^{-1}$ , in equation (18). It is evident that the modest temperature difference between the poles and the equator needed to account for observations can be easily obtained for field strengths above a few  $10^{10} \text{ G}$ . The corresponding shock temperatures are also in the range of the observed values ( $\sim 4.10^8 \text{ K}$ ).

The problems of energy storage and transfer associated with the impulsive phase of the burst are also present in the pulsating phase. The suggestions, by Ramaty et al. (1980), of mechanical energy storage and transfer, appears to provide, for this phase too, the best solution to the problem. Since gravitational radiation must damp all the the non-radial modes on short time scales (those of the duration of the impulsive phase), the pulsed emission would most likely be associated with the energy stored in the radial mode of oscillation. The reduced luminosity can then be accounted for in terms of the decreased acoustic matching between the neutron star core and its heated atmosphere. The acoustic matching is considerably better during the impulsive phase, when presumably a large fraction of the oscillatory energy is in the higher frequency modes. This energy can be transmitted efficiently through the surface density gradient and heat the atmosphere. The transmissivity is expected to be significantly reduced for the longer wave length modes of the pulsating phase, resulting in less efficient energy transfer and hence lower luminosity.

The magnetic field is expected to play an important role in this matching. The radial mechanical motion will shake the magnetic field lines

producing outward propagating Alfvén waves thus providing a coupling capable of tapping the energy of the radial oscillatory modes. Setting aside for the moment the question of transmissivity, one can estimate roughly the energy flux carried by these waves from  $F \approx \delta B (B/4\pi)cA$ . Since generally it is expected that  $\delta B/B \sim \delta R/R$ , and  $\delta B$  is not perpendicular to  $B$ , the above estimate gives

$$F = \frac{\delta R}{R} \frac{B^2}{4\pi} c 4\pi R^2 \approx 10^{43} \text{ erg s}^{-1}$$

assuming  $\delta R/R \sim 10^{-3}$  as argued earlier and using values for  $B$  and  $R$  typical of neutron stars, i.e.,  $10^{12}$  G and  $10^6$  cm. This value of  $F$  is essentially identical with that observed in the pulsating phase, provided the source is in the LMC. These waves are of course expected to further steepen into shocks providing the observed radiation as outlined earlier.

Eventually the radial oscillations will also damp on much longer time scales, due to nuclear processes in the neutron star core (see for example Langer and Cameron 1969) thus terminating the burst. Since the energy needed in the pulsating phase is provided by shock heating in a way very similar to that of the impulsive phase, the emission mechanism for this phase should be the same as that for the original spike (Katz 1982). An additional feature of the oscillating phase is the difference in temperature between the main pulses and the interpulses. Mazets et al. (1982) report average values of 35.5 and 31.4 keV respectively. In view of the overall uncertainties of the problem, one could possibly attribute this to either asymmetry in the initial corequake, favoring heating of a particular area of the neutron star, or asymmetry in the star's magnetic field resulting in uneven heating of the magnetic poles. (This is also suggested by the pulse profile of Fig. 1, which

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shows a deeper minimum following the main pulse than following the interpulse; (F. C. Michel, private communication).

## V. DISCUSSION AND CONCLUSIONS

We have examined in greater detail the basic features of the model for the 5 March 1979 gamma ray burst suggested by Ramaty et al. (1980), assuming a physical association of the burst with the supernova remnant N49. We accept the basic features of their model regarding the energy source of the burst (corequake of a neutron star), the energy storage (mechanical in vibrations) and the transfer of that energy by acoustic waves steepening into shocks in the atmosphere. We have in turn examined the characteristics of these shocks in greater detail assuming thermodynamic equilibrium behind the shock (appropriate for the high density regions below the emission layer) and demanding that the energy flux through the shock matches the burst luminosity (assumed to be located in N49).

Assuming values for the density typical to those expected for neutron star crusts ( $\rho \approx 10^2 - 10^4 \text{ g cm}^{-3}$ ) and velocities of the order of the sound speed in neutron stars ( $\sim 4 \cdot 10^4 - 10^5 \text{ km s}^{-1}$ ) we obtain shock luminosities which are in good agreement with observation, providing that a substantial fraction of the neutron star surface radiates. Under the assumption of thermodynamic equilibrium we have calculated the corresponding postshock temperatures and pair densities for various values of velocity and preshock density. The downstream temperature,  $T_{e2}$ , as shown in Fig. 2, depends on the velocity, density and magnetic field; however  $T_{e2}$  is almost independent of these quantities for constant  $F_{sh}$ , indicating that the shocks are radiation dominated and that most of the shock energy is transferred to the radiation field. Therefore, as expected, black body emission at the downstream temperature,  $T_{e2}$ , produces the observed luminosity if the burst is in the LMC

and the radiation is emitted from a sizable fraction of the neutron star surface.

The large duty cycle implied by the time profile of the pulsating phase strongly argues in favor of emission over most of the surface of the star and in the context of this model suggests that the source is indeed as distant as the LMC. If the 5 March 1979 burst luminosity were  $10^4$  times smaller, corresponding to a galactic event, involving the whole neutron star surface area for the emission as argued above, the corresponding shocks would have much lower temperatures and no pairs would be produced. This shock model would therefore not be compatible with a nearby event.

The assumption of thermodynamic equilibrium is of course not valid when the shocks break through the atmosphere and the optical depth becomes  $\sim 1$ . Therefore the present model cannot provide a detailed account of the observed spectrum. The detailed interpretation of the spectrum is further complicated by the apparent strong temporal evolution during the first 150 ms of the burst (Hurley 1983). The model does provide reasonable estimates of the conditions and energetics in the denser regions where thermodynamic equilibrium prevails. In addition, the ratio of pair annihilation energy to that emitted in the continuum is in good agreement with observations for values of  $F_{sh}$  corresponding to the observed luminosity. If  $F_{sh}$  were substantially less, as in the pulsating phase or for a galactic burst, no pairs would be produced (under the assumptions presently employed). Since no radiative transfer effects associated with the last optical depth of the radiation are presently taken into account, no strong claims can be made relating these pairs to the observed annihilation feature, however the agreement to observations lends further credence to the model.

Finally, this shock heating model provides a natural explanation for the

pulsating phase through the enhanced heating of the polar regions due to the dipole magnetic field and the rotation of the neutron star. The lower values of  $F_{sh}$  inferred from the lower pulsation luminosity again produce temperatures consistent with observations if the source is in the LMC.

The model elaborated upon here, while explaining in general terms the properties of this event, involves large scale readjustments in the structure of relatively old neutron star cores that must be quite rare, implying that some other mechanism powers the more numerous, less energetic galactic gamma ray bursts.

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## FIGURE CAPTIONS

Fig. 1. Initial sharp pulse and first several pulsations of the 5 March 1979 gamma ray burst. The pulse-interpulse structure is evident. Data are from Venera 11 and 12 and the figure is taken from Mazets et al. (1982).

Fig. 2. Downstream plasma temperature,  $T_{e2}$ , versus upstream density,  $\rho_1$ . Solid lines are curves for various shock velocities,  $u_1$ , with  $B_1 = 10^{11}$  G and  $T_{p1} = T_{e1} = 10^5$  K. Dashed lines show values of  $u_1 = 4 \times 10^4$  and  $10^5$  km s $^{-1}$  with  $B_1 = 0$  and  $T_{p1} = T_{e1} = 10^5$  K. The curves labeled (a), (b) and (c) correspond to  $F_{sh} = 2 \times 10^{45}$ ,  $1 \times 10^{45}$  and  $5 \times 10^{44}$  erg s $^{-1}$  respectively.

Fig. 3. Downstream positron density,  $n_+$ , versus upstream density,  $\rho_1$ . Solid lines are curves for various shock velocities,  $u_1$ , with  $B_1 = 10^{11}$  G and  $T_{p1} = T_{e1} = 10^5$  K. Dashed lines show values of  $u_1 = 4 \times 10^4$  and  $10^5$  km s $^{-1}$  with  $B_1 = 0$  and  $T_{p1} = T_{e1} = 10^5$  K. The curves labeled (a), (b) and (c) correspond to  $F_{sh} = 2 \times 10^{45}$ ,  $1 \times 10^{45}$  and  $5 \times 10^{44}$  erg s $^{-1}$  respectively. The dotted line shows the effect of increasing the upstream temperature to  $10^9$  K for  $u_1 = 10^5$  km s $^{-1}$  and  $B_1 = 10^{11}$  G.

Fig. 4. Compression ratio,  $r$ , versus upstream density,  $\rho_1$ . Solid lines are for  $B_1 = 10^{11}$  G. Upper dashed line is for  $B_1 = 0$  and  $u_1 = 10^5$  km s $^{-1}$  while lower dashed line is for  $B_1 = 0$  and  $u_1 = 4 \times 10^4$  km s $^{-1}$ . The curves labeled (a) and (b) correspond to  $F_{sh} = 2 \times 10^{45}$  and  $1 \times 10^{45}$  erg s $^{-1}$  respectively for an upstream temperature of  $10^5$  K and  $B_1 = 10^{11}$  G. Curves (a') and (b') are the same as (a) and (b) with an upstream temperature of  $10^9$  K.

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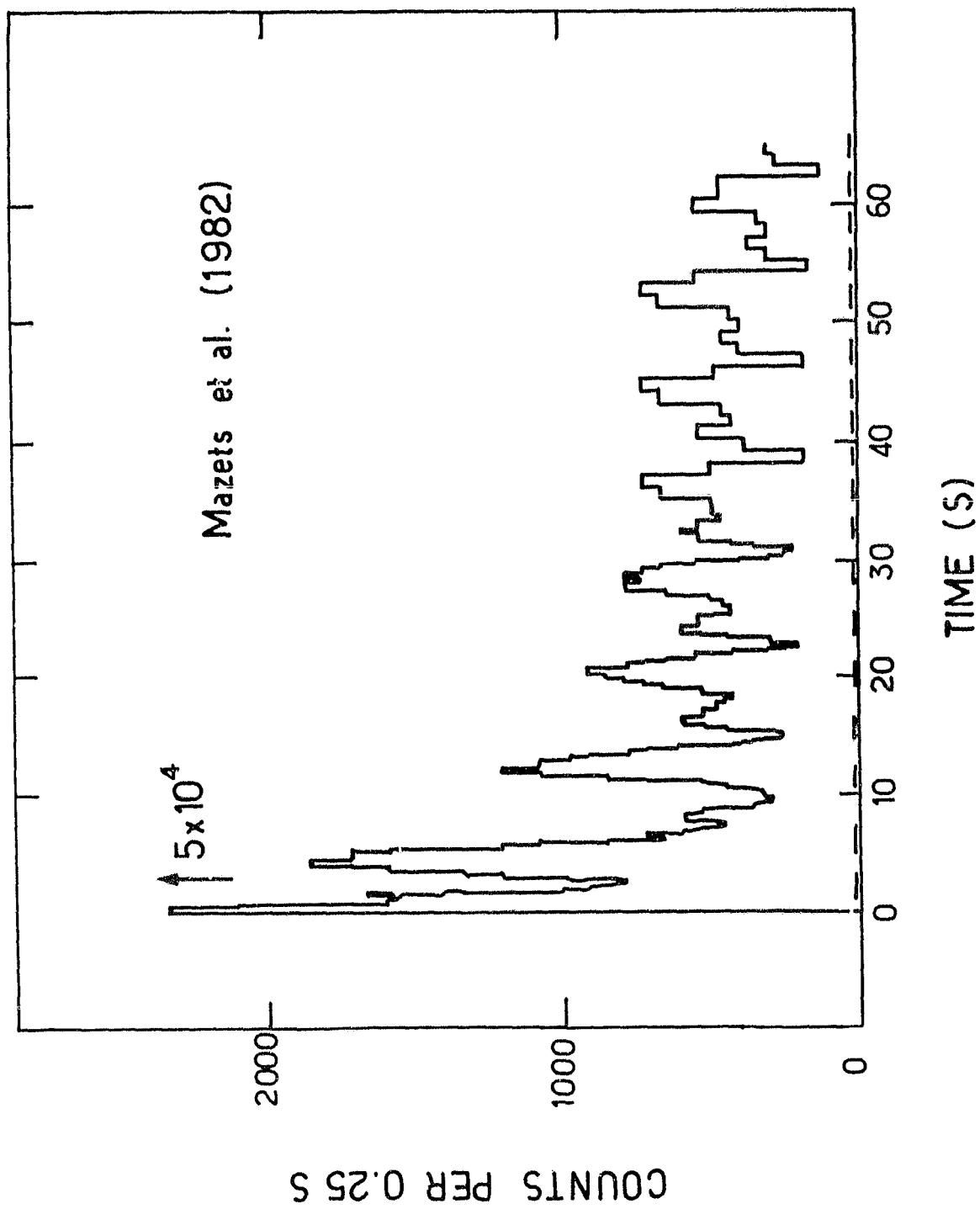
Fig. 5. Ratio of equatorial to polar (equivalent to  $B = 0$ ) temperatures versus upstream magnetic field,  $B_1$ . The shock luminosity,  $F_{sh} = 1 \times 10^{45}$  erg  $s^{-1}$ . Dashed line indicates minimum temperature ratio compatible with observations.

TABLE I

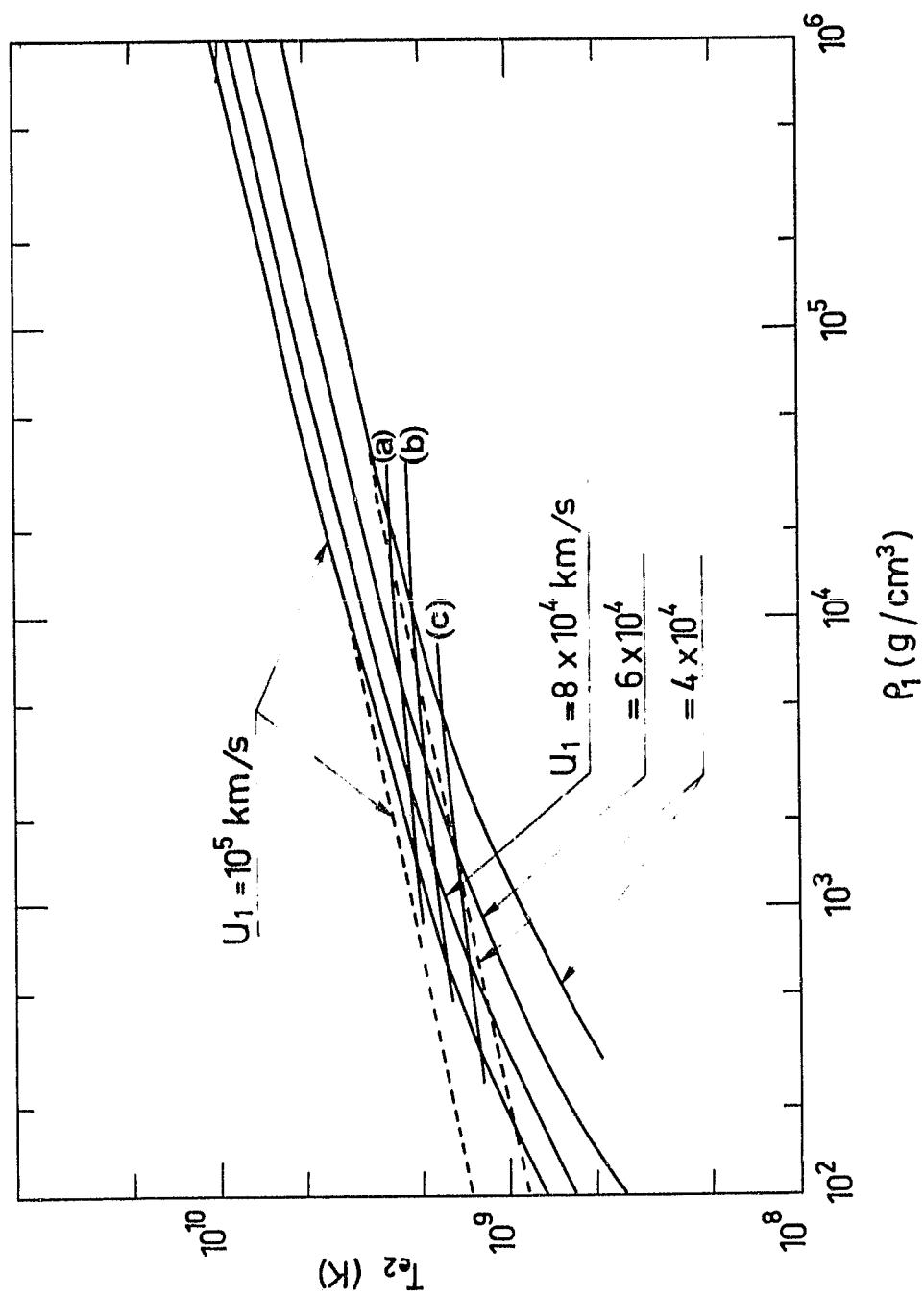
Input parameters						Energy flux (%)				n+27	
$F_{8h}$	$u_1$	$\hat{p}_1$	Magnetic field	$e^-, e^+$	Mass (a)	Total	Pair rest	Photon	a	$\tau^4$	
(erg/s)	(km/s)	(g/cm <sup>3</sup> )				b			b	9	
$1 \times 10^{43}$	$1 \times 10^4$	$6.7 \times 10^3$	56	14	0	6.9	0	0	0		
	$2 \times 10^4$	$8.4 \times 10^2$	75	2.5	0	7.9	0	0	0		
$5 \times 10^{44}$	$4 \times 10^4$	$5.2 \times 10^3$	13	11	3.2	67	0.05	0.9	0.9		
	$1 \times 10^5$	$3.4 \times 10^2$	34	4.7	2.7	60	0.05	0.8	0.8		
$1 \times 10^{45}$	$4 \times 10^4$	$1.0 \times 10^4$	10	16	4.7	68	0.07	1.3	1.3		
	$1 \times 10^5$	$6.7 \times 10^2$	22	10	5.5	66	0.08	1.5	1.5		
$2 \times 10^{45}$	$4 \times 10^4$	$2.1 \times 10^4$	5.4	20	5.4	68	0.08	1.5	1.5		
	$1 \times 10^5$	$1.3 \times 10^3$	13	16	7.8	69	0.11	2.1	2.1		

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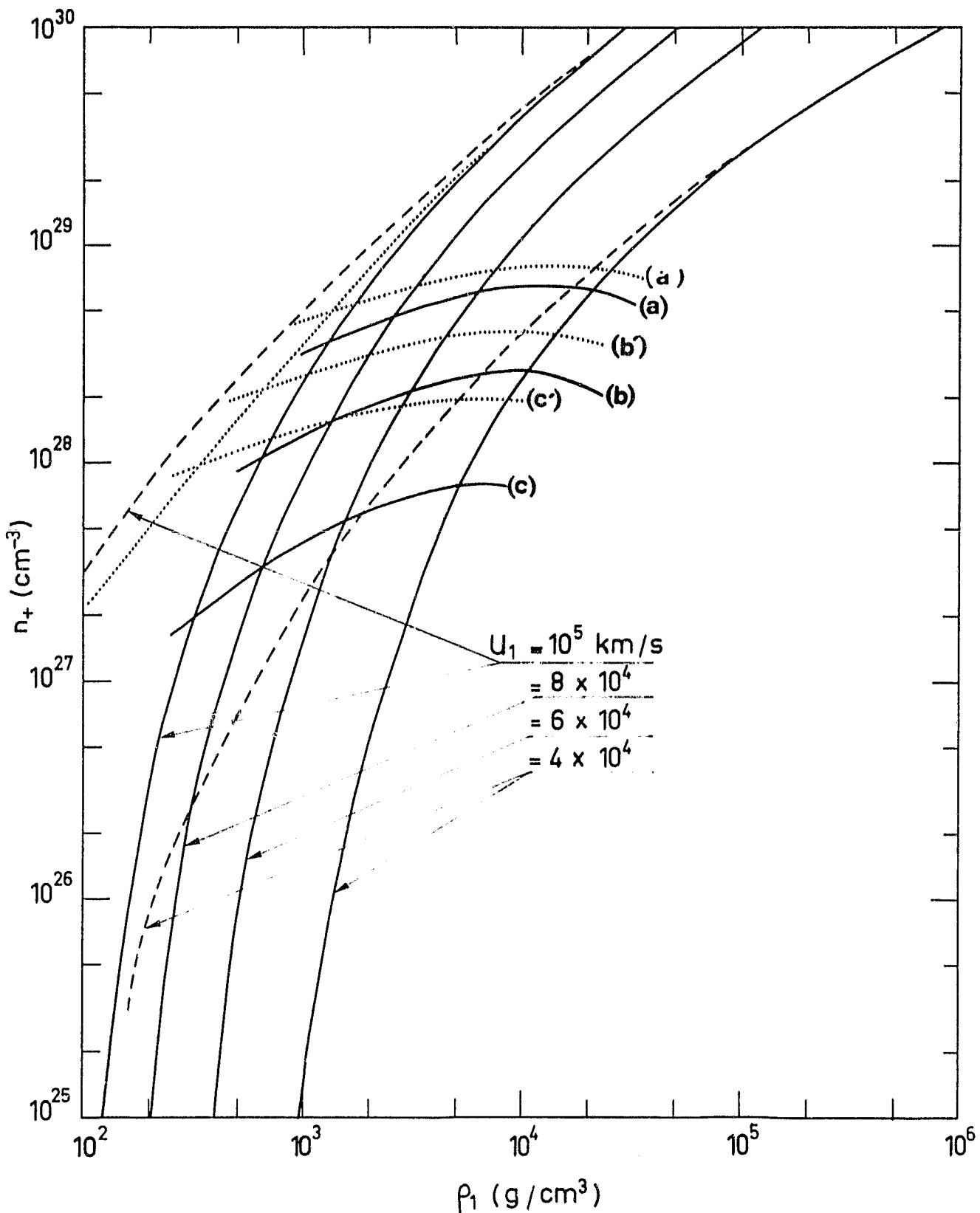
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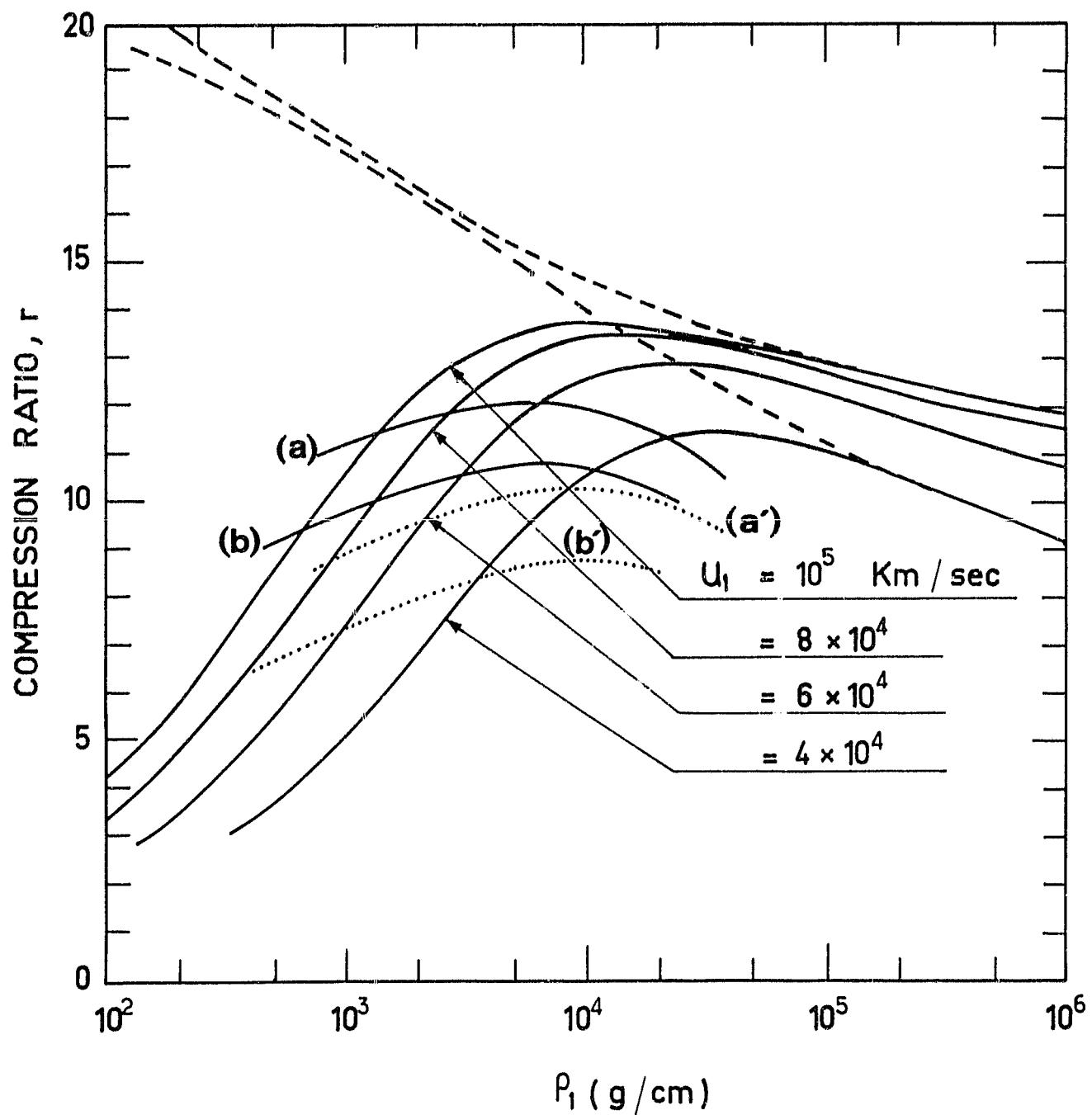
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